

EE-527: Microfabrication

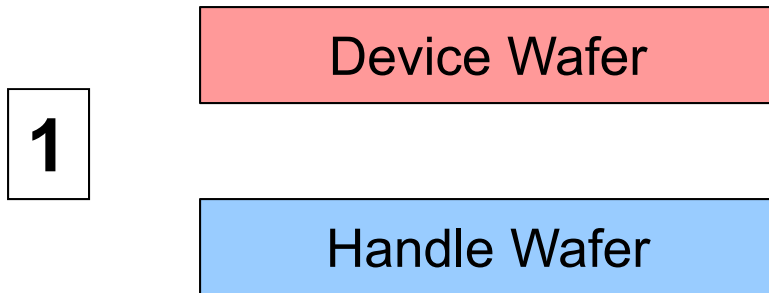
Wafer Bonding

Outline

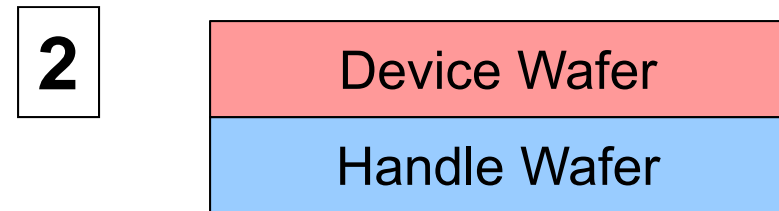
- Forces between surfaces – physical chemistry of bonding
 - Hydrophilic silicon surfaces
 - Hydrophobic silicon surfaces
- Silicon fusion bonding
 - Room temperature bonding
 - High temperature bonding
- Bonding of dissimilar materials
 - Anodic bonding of borosilicate glass to silicon
 - Silicon on sapphire (SOS)
 - Silicon on insulator (SOI)
 - GaAs on silicon (epitaxial liftoff - ELO)
- Device applications

Overview of the Wafer Bonding Process

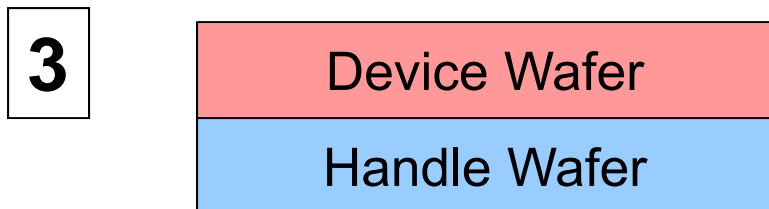
Surface Preparation and Cleaning



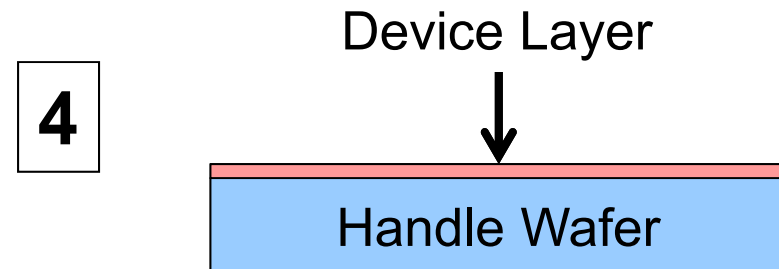
Room Temperature Bonding



High Temperature Annealing



Wafer Thinning



Advantages of Wafer-to-Wafer Bonding

- Allows much more complex structures to be constructed, especially those that require multiple cavities at different depths.
- Provides great versatility in sealing and packaging.
- Allows (some) combinations of dissimilar materials to be used, often to great advantage for processing ease or system performance.

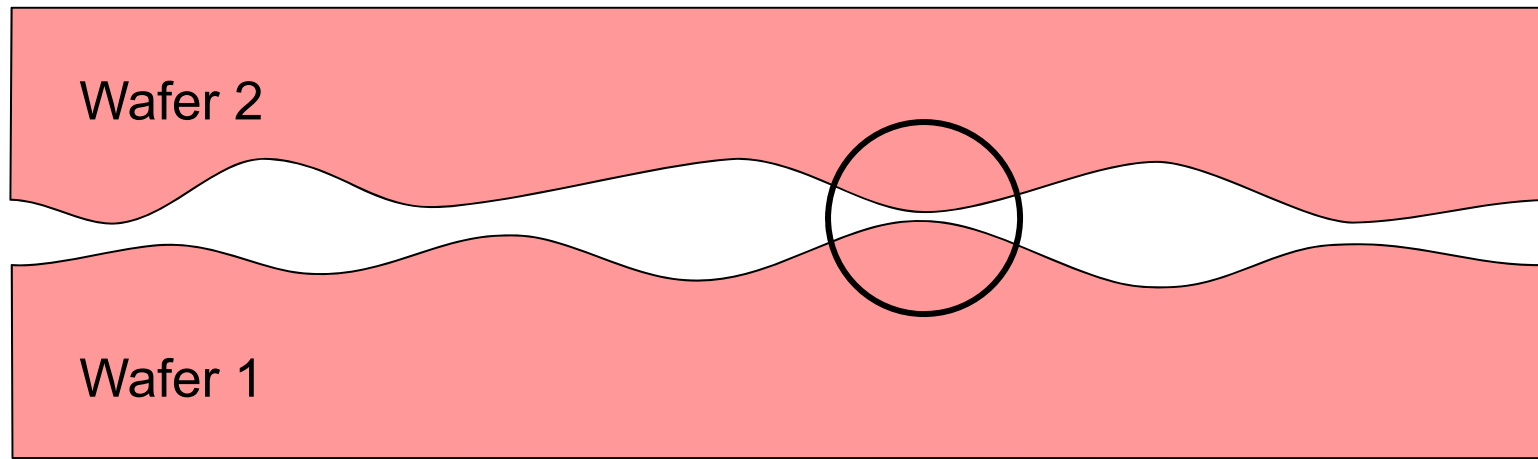
Challenges in Wafer-to-Wafer Bonding

- Cleanliness.
- Surface flatness.
- Uniformity.
- Gas bubbles.
- Limited to relatively small wafers (6-inch or less).
- Alignment of wafers to each other is difficult.
- Low throughput.

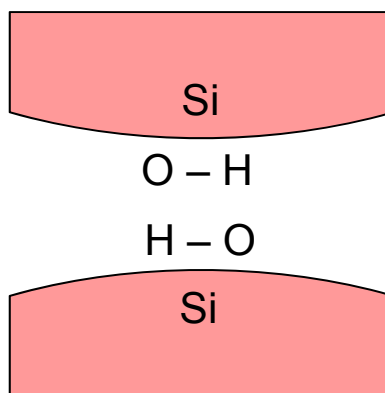
Surface Forces that Create Bonding

- van der Waals forces:
 - $F_v = A / 6\pi d^3$, d = separation distance, A = Hamaker constant.
 - Hydrogen bonding (dipole – dipole attraction) is quite strong, especially with H – O, H – F, and H – N bonds. Water molecules can link together using these forces.
- Capillary forces:
 - Present only if the surface contact wetting angle is less than 90° .
 - Liquid must bridge the two surfaces and form a concave meniscus in order to create an attractive force between the two surfaces.
- Electrostatic forces:
 - These are strongest in ionic materials with permanent ionic charges.
 - F_i decays exponentially with d , Coulomb's Law.

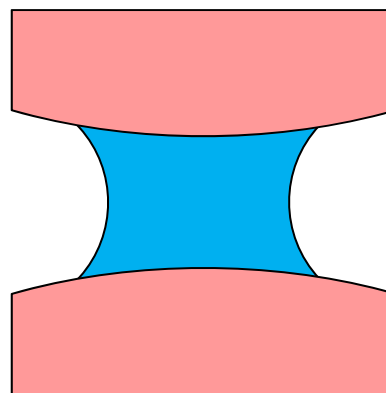
Surface Forces in Wafer Bonding



van der Waals forces



capillary forces



electrostatic forces

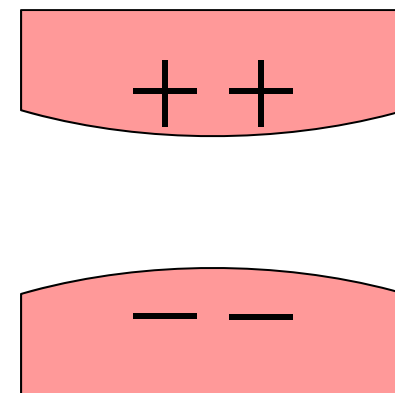


Figure after Tong and Gösele, *Semi Wafer Bonding*, 1999.

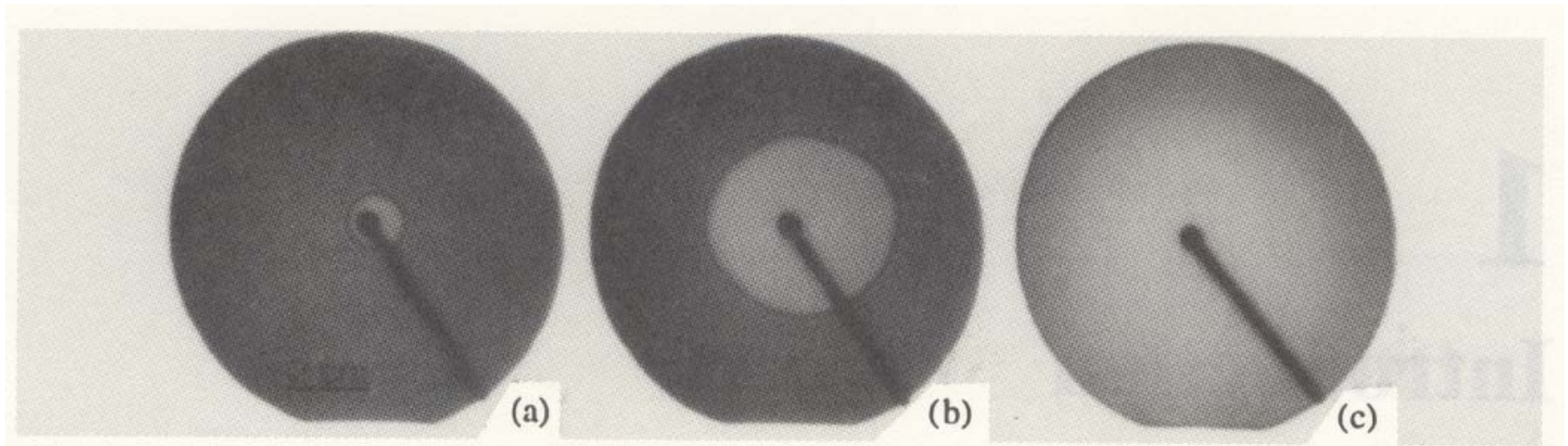
Bonding Surfaces are Never Perfect

- It is impossible to bond two single crystal materials and end up with a single crystal.
- Imperfections limit this:
 - Surface steps.
 - Surface voids.
 - Surface bumps.
 - Surface contaminants that change the flatness and the composition.
- Bonding requires the two surfaces to accommodate for these imperfections:
 - Flexing of the wafer (large scale strain).
 - Distortion of the bonding zone (local strain).
 - Variable filling by an intermediate bonding material.

Bonding Area Propagation

- During bonding, the wafers flex.
- As the two surfaces pull together to create the bond, the bonding zone propagates across the wafer. This is equivalent to the propagation of a closing crack.
- De-bonding can sometimes be accomplished, and is equivalent to the propagation of an opening crack, with the wafers also flexing as this proceeds.
- Bonding needs to be initiated at some point. Most bonding apparatus start by applying pressure at the center of the wafer and allowing the bonding area to propagate outward. This increases the chances of working out any trapped gas bubbles.

Propagation of Wafer Bonding



Infrared camera view of bonding propagating from the tong point in the center outward to the edges of two silicon wafers.

Hydrophilic Surface Bonding in Silicon

- van der Waals bonding requires hydroxyl (--OH) groups on the surface to which water molecules can attach.
- Native oxides and thermally grown oxides terminate in oxygen atoms which must be hydrated to form a hydrophilic surface.
- $\text{Si--O--Si} + \text{HOH} \leftrightarrow \text{Si--OH} + \text{HO--Si}$.
- Surface Si--OH are called silanol groups.
- Oxide Si--O--Si are called siloxane bonds.
- Siloxane to silanol conversion is reversible up to $\sim 425^\circ\text{C}$.
- If both wafer surfaces are sufficiently flat and hydrophilic, they will bond together at room temperature with simple pressure to squeeze out the air and/or water.

Hydrophobic Surface Bonding in Silicon

- SiO_2 on the surface of a Si wafer can be stripped with a dilute aqueous HF etch solution.
- Upon removal from the HF etch solution, the Si surface will be terminated in mostly hydrogen atoms, Si–H, but also a few fluorine atoms, Si–F, $\sim 10^{14} \text{ cm}^{-2}$.
- This surface is hydrophobic, and water droplets can be seen to bead up on it. This is usually a good visual test that a wafer has had its oxide successfully removed.
- Si–F bonds are strongly ionic ($\sim 45\%$ ionic character), and provide sites for HF bridging molecules which can create room temperature bonding.

Wafer Bonding Apparatus – Queen's University, Belfast

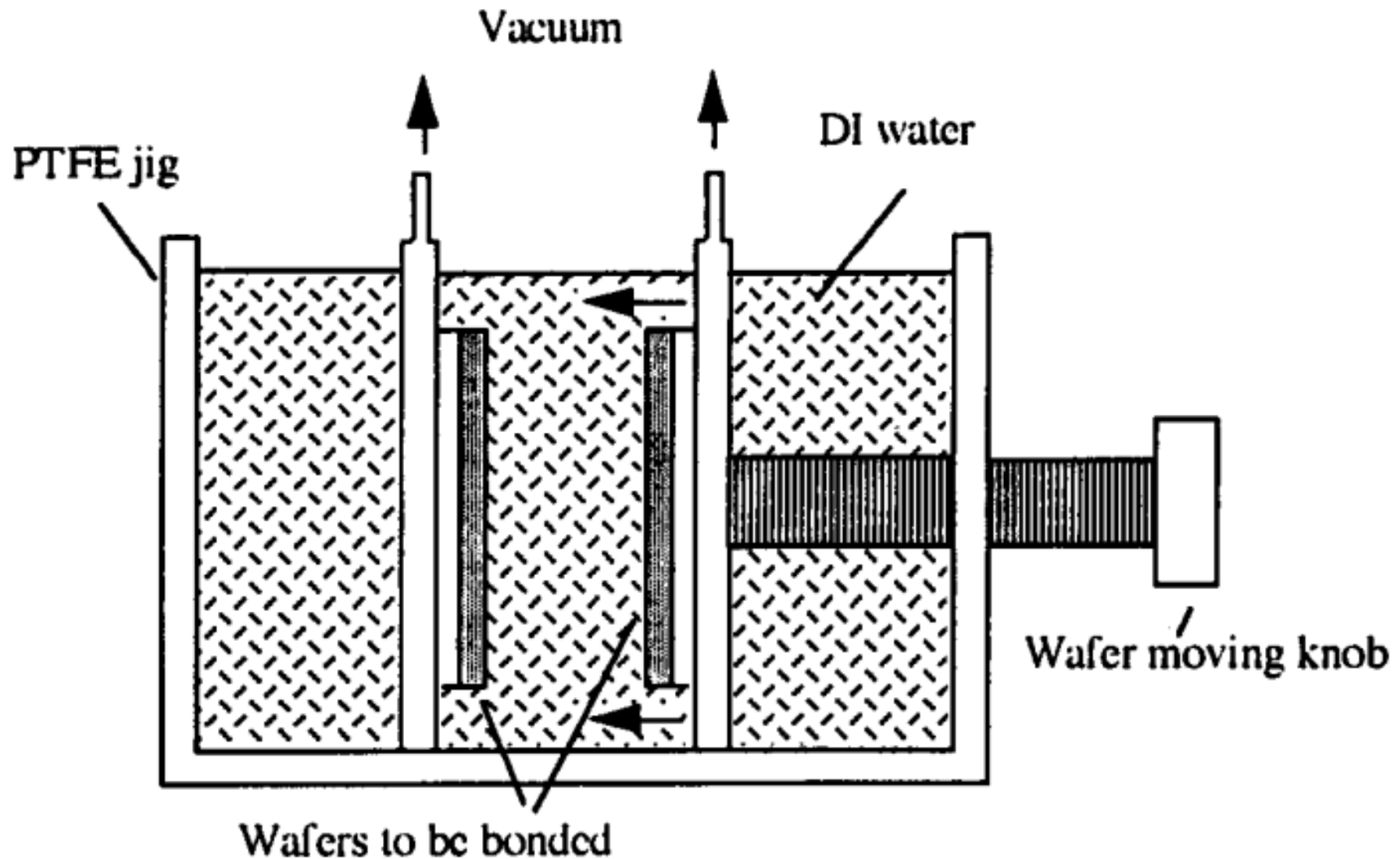


Figure from Tong and Gösele, *Semi Wafer Bonding*, 1999.

Wafer Bonding Apparatus – UC Davis

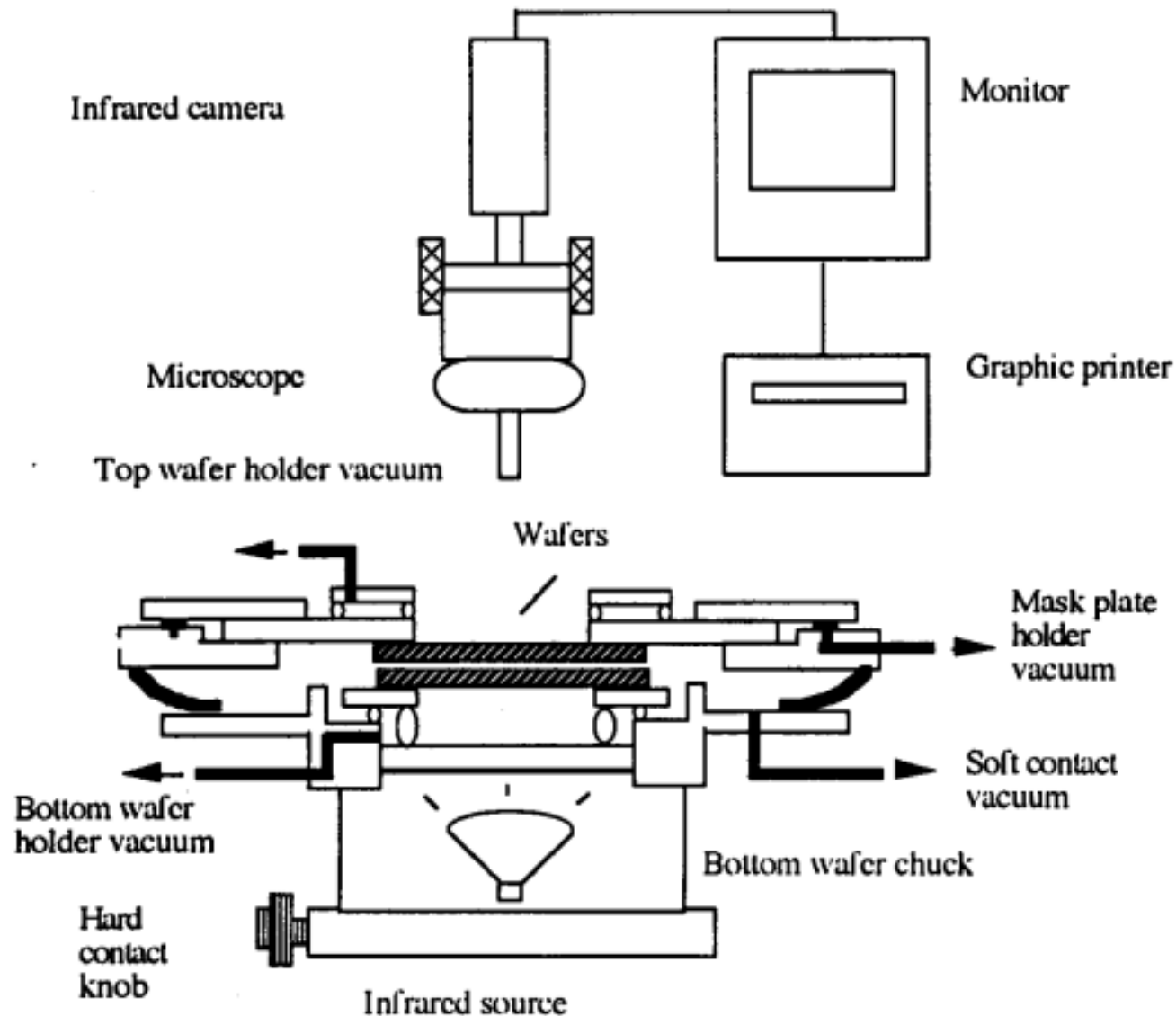


Figure from Tong and Gösele, *Semi Wafer Bonding*, 1999.

Wafer Bonding Apparatus – Low Vacuum

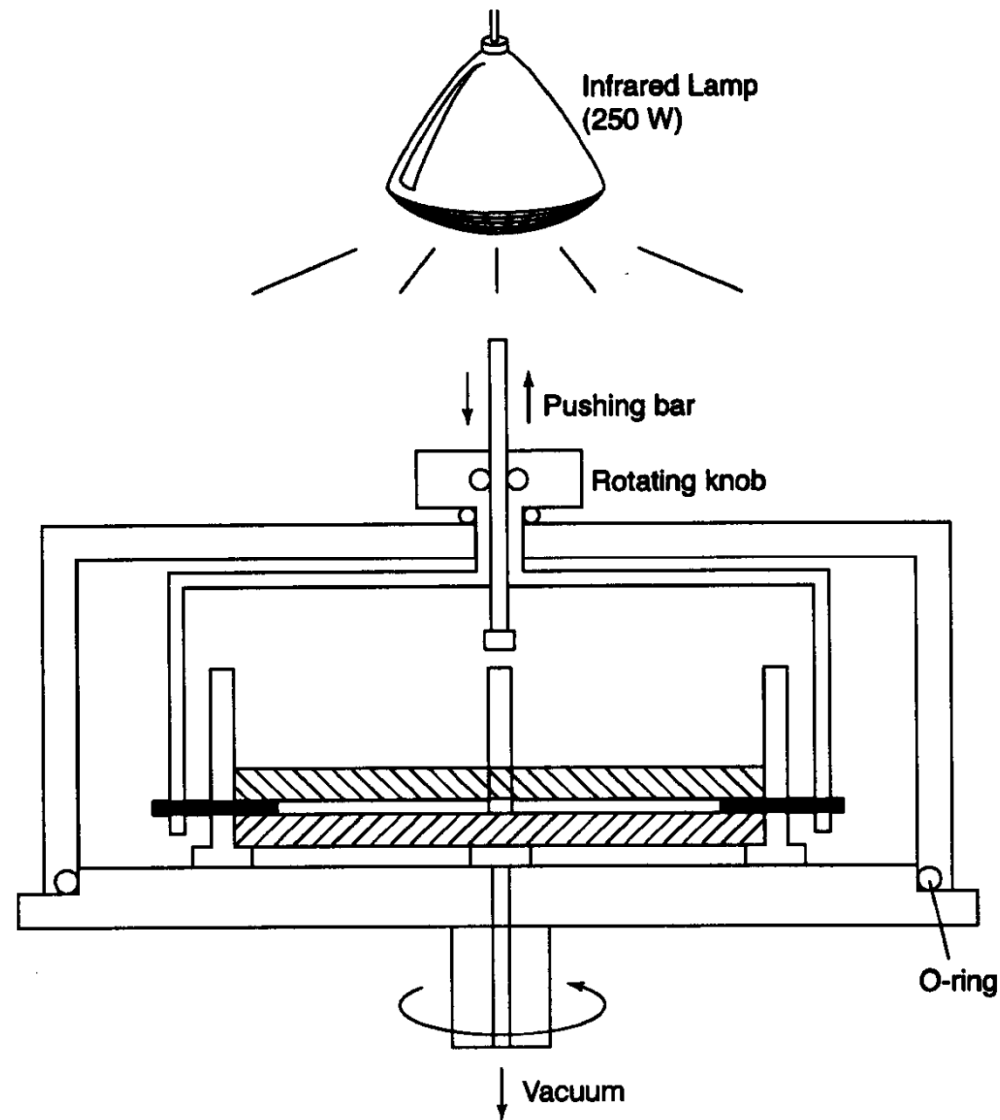


Figure from Tong and Gösele, Semi Wafer Bonding, 1999.

Low Vacuum Bonding Sequence – A, B

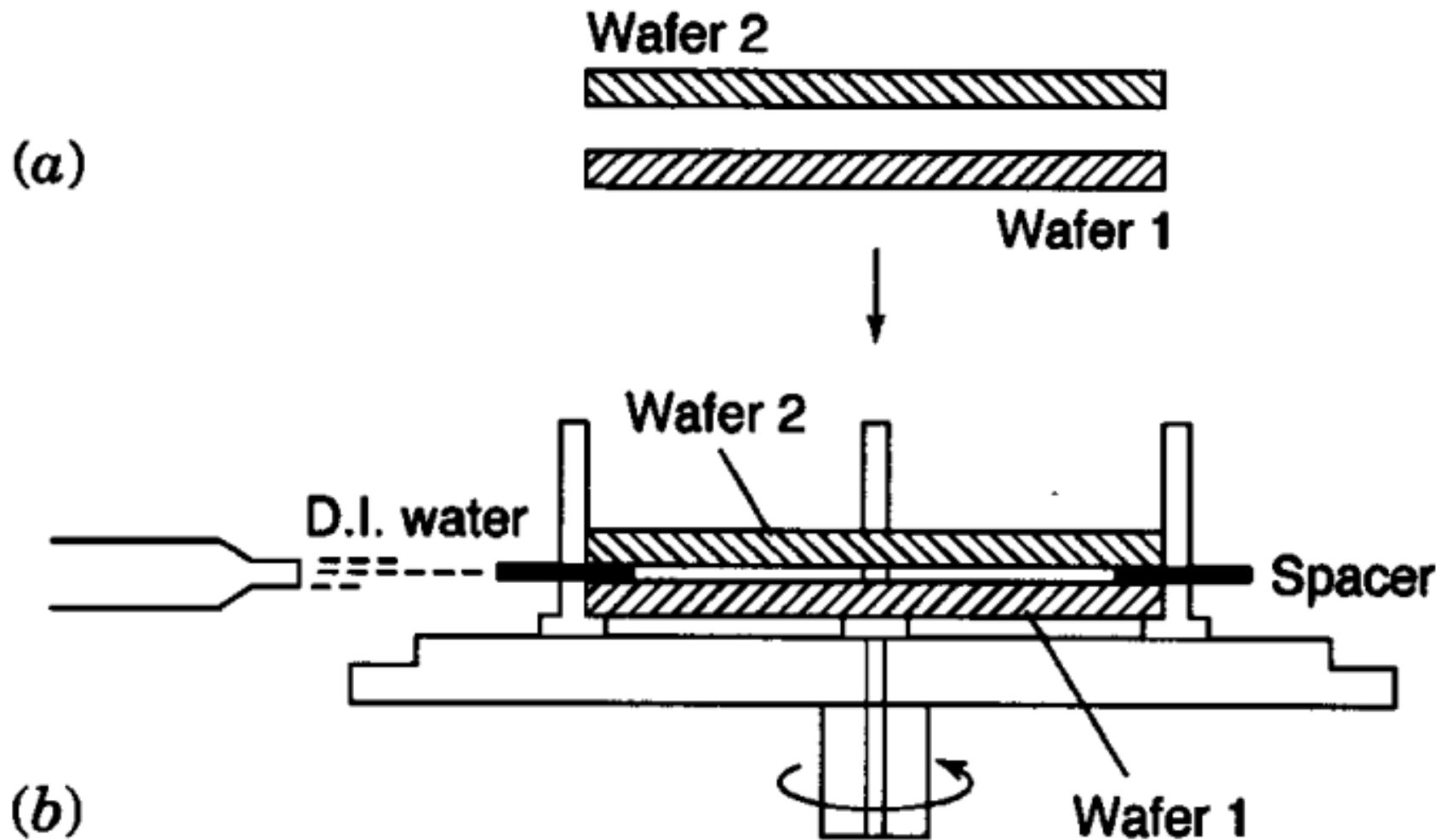


Figure from Tong and Gösele, *Semi Wafer Bonding*, 1999.

Low Vacuum Bonding Sequence – C

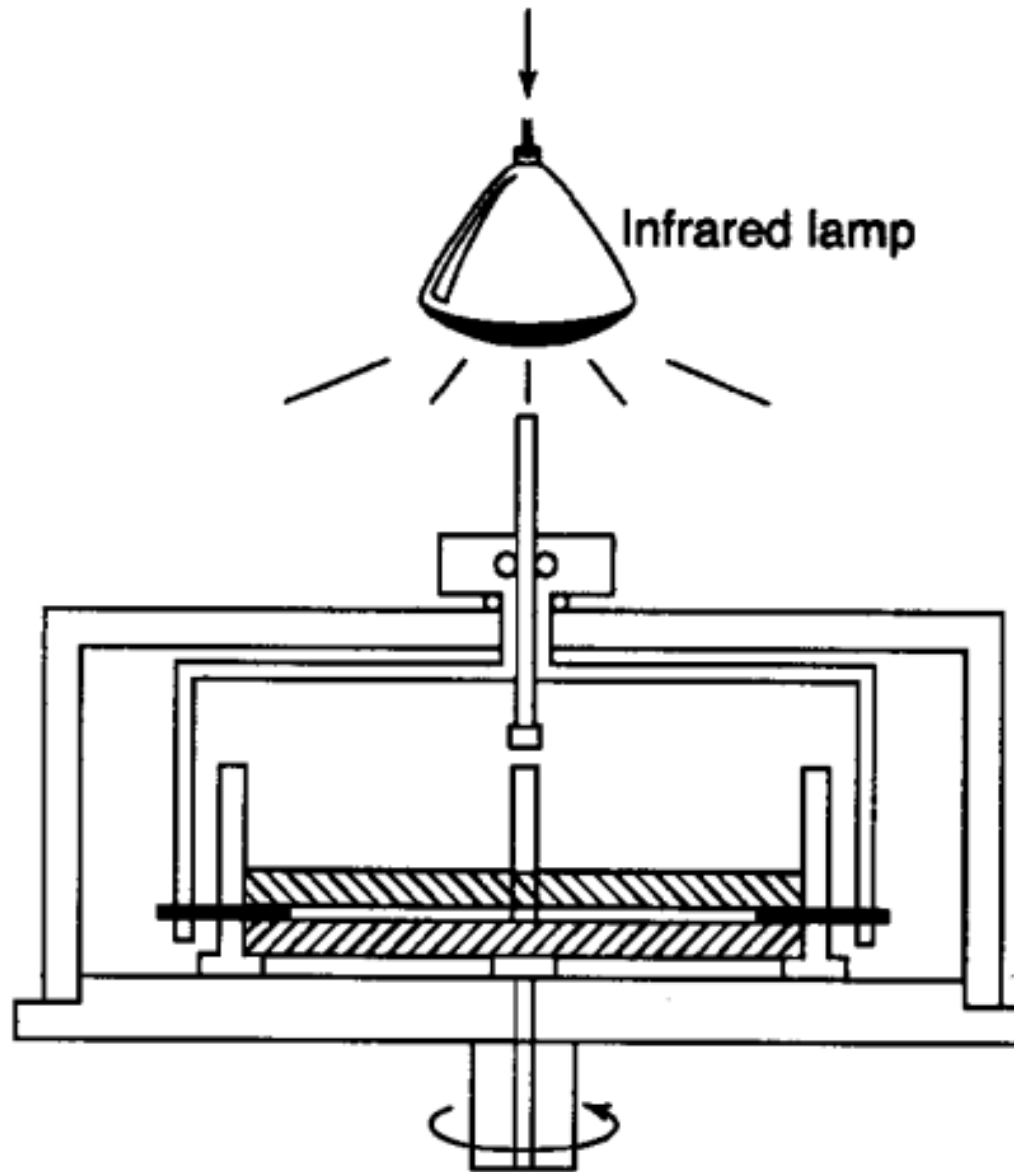


Figure from Tong and Gösele, Semi Wafer Bonding, 1999.

Low Vacuum Bonding Sequence – D, E

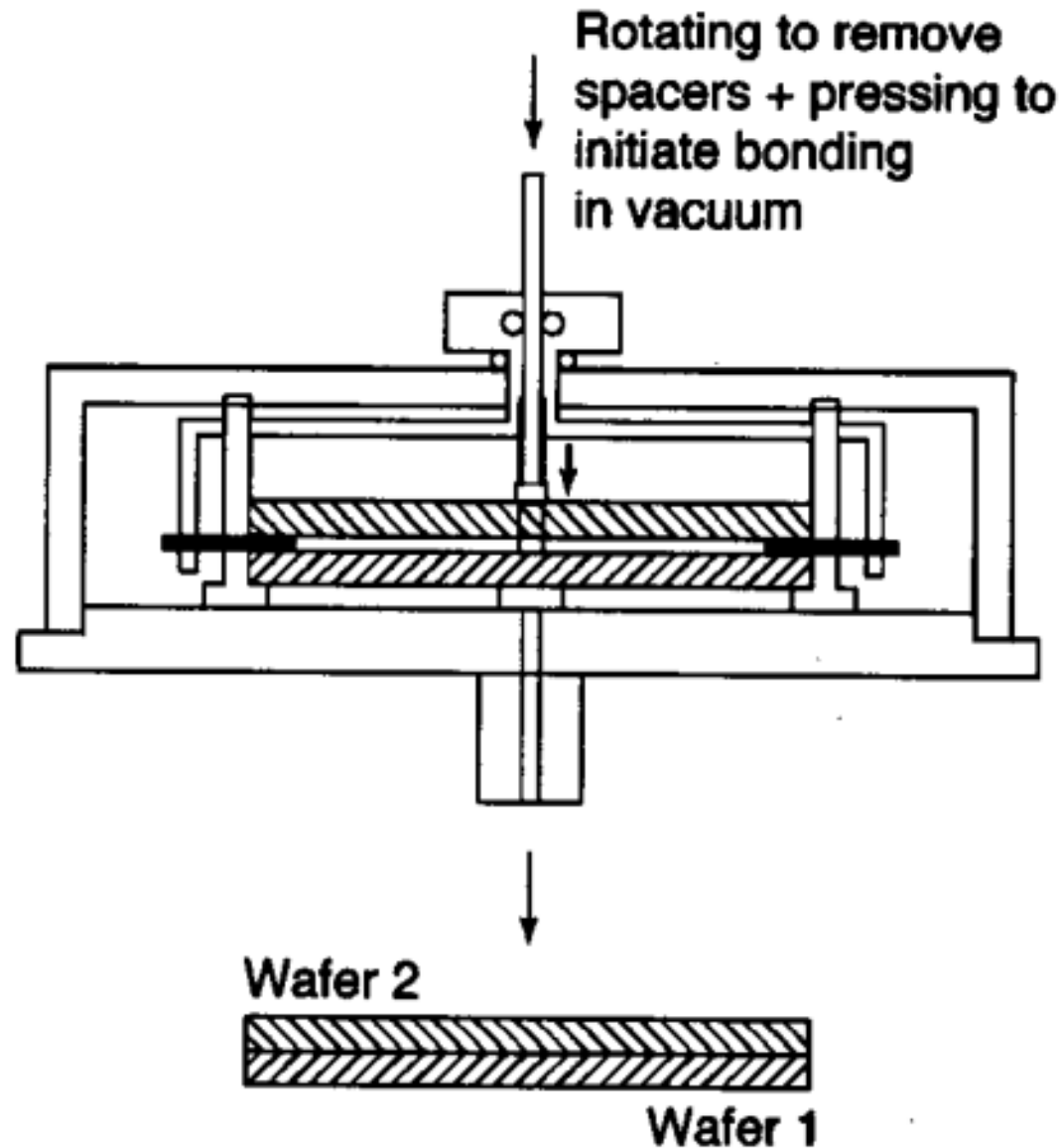


Figure from Tong and Gösele, *Semi Wafer Bonding*, 1999.

Thermal Annealing of Bonded Wafers

- After room temperature (RT) bonding (sometimes known as “tacking”), wafer pairs are usually given a thermal treatment to increase the bond strength.
- This varies considerably, depending upon the application.
- Bond strength is measured as the surface energy required to separate the joined surfaces. Examples:
 - Hydrophobic Si/Si with RT tack: 25 mJ/m²
 - Hydrophobic Si/Si with 300°C anneal: 140 mJ/m²
 - Hydrophobic Si/Si with 700°C anneal: 2100 mJ/m²
 - Hydrophilic Si/Si with RT tack: 135 mJ/m²
 - Hydrophilic Si/Si with 300°C anneal: 1200 mJ/m²
 - Hydrophilic Si/Si with 800°C anneal: 2100 mJ/m²
 - SiO₂/sapphire with 150°C anneal: 2500 mJ/m²

Thermal Annealing of Bonded Silicon Wafers

- Hydrophilic surfaces:
 - RT to 110°C: interfacial water rearrangement.
 - 110°C to 150°C: polymerization of silanol groups; significant increase in surface energy to $\sim 1200 \text{ mJ/m}^2$.
 - 150°C to 800°C: bonding limited by contact area; no increase in bond strength.
 - 800°C to 1200°C: oxide reflows; bond strength increases to $\sim 2100 \text{ mJ/m}^2$.
- Hydrophobic surfaces:
 - RT to 150°C: stable state; no increase in bond energy.
 - 150°C to 300°C: HF bond rearrangement; bond energy increases up to $\sim 140 \text{ mJ/m}^2$.
 - 300°C to 700°C: Hydrogen desorbs and Si–Si covalent bonds form; bond strength increases from ~ 140 to $\sim 2100 \text{ mJ/m}^2$ over this range.
 - 700°C to 1200°C: Si atoms diffuse at surface giving complete bonding.

TEM of Hydrophilic (SiO_2) Bonded Si Wafers

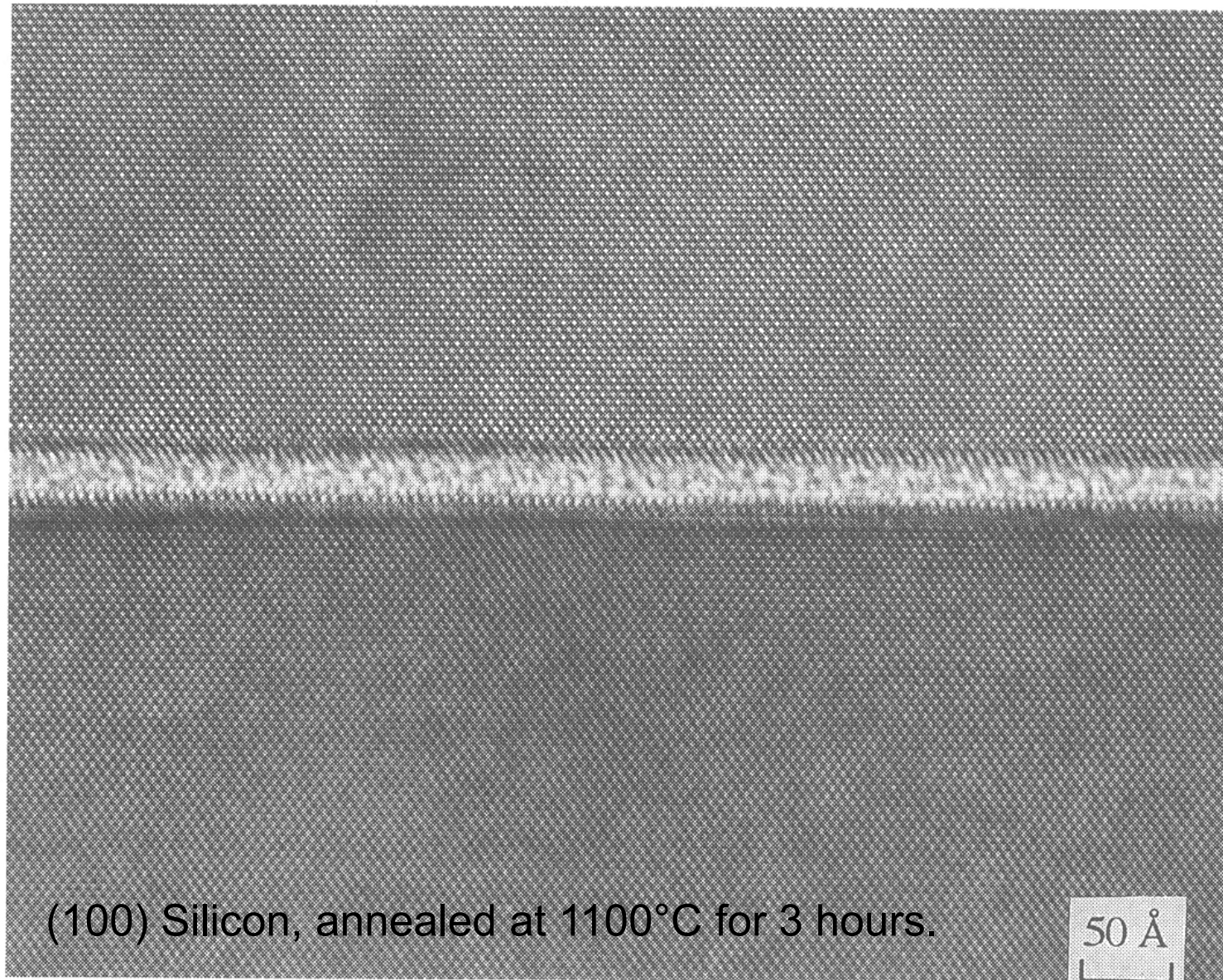


Figure from Tong and Gösele, Semi Wafer Bonding, 1999.

TEM of Hydrophobic (Si) Bonded Si Wafers

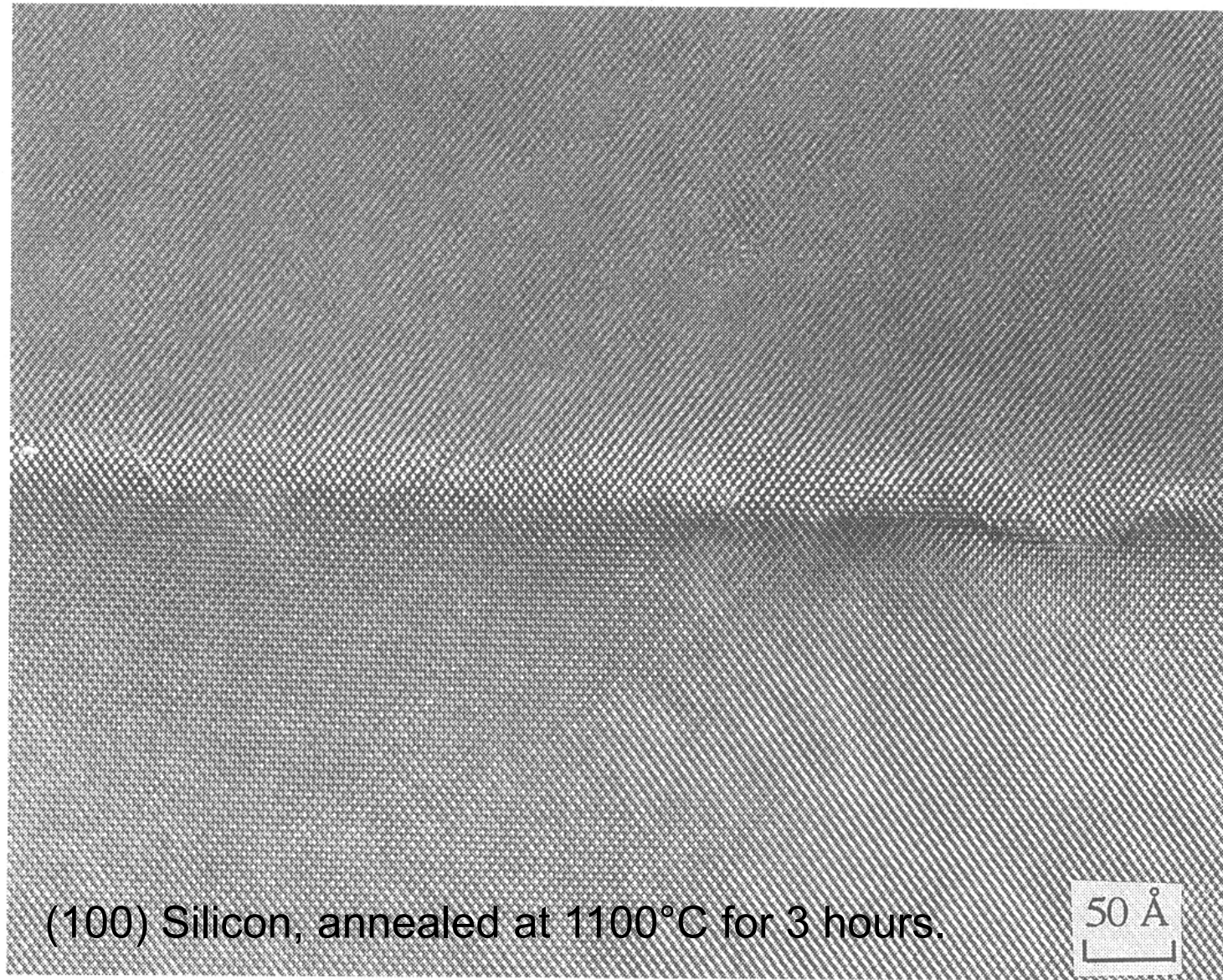


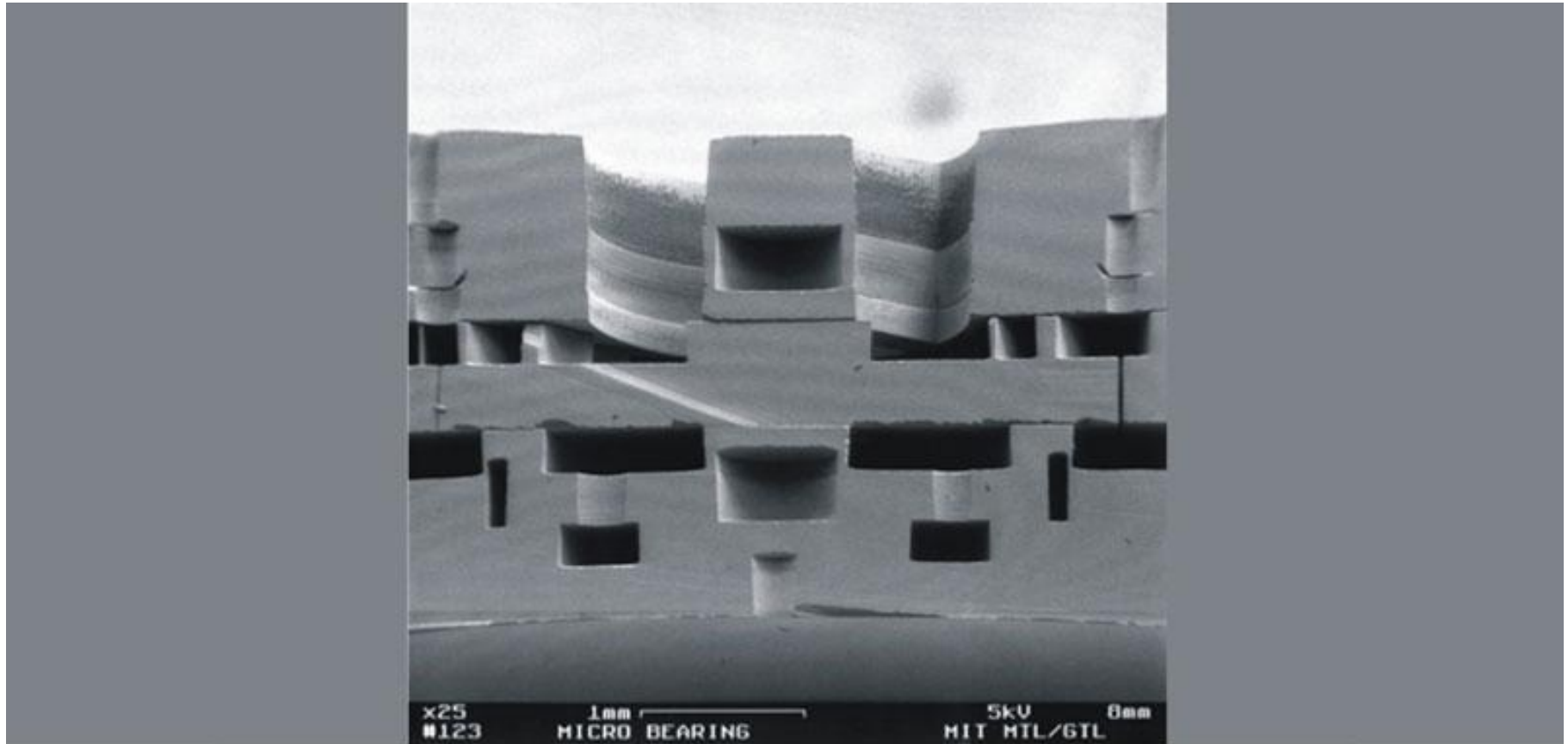
Figure from Tong and Gösele, Semi Wafer Bonding, 1999.

EVG Wafer Bonder



Figure from EVG.

MIT Micro Turbine Engine Using Wafer Bonding



8-layer direct bond cross-section.
Courtesy of MIT.

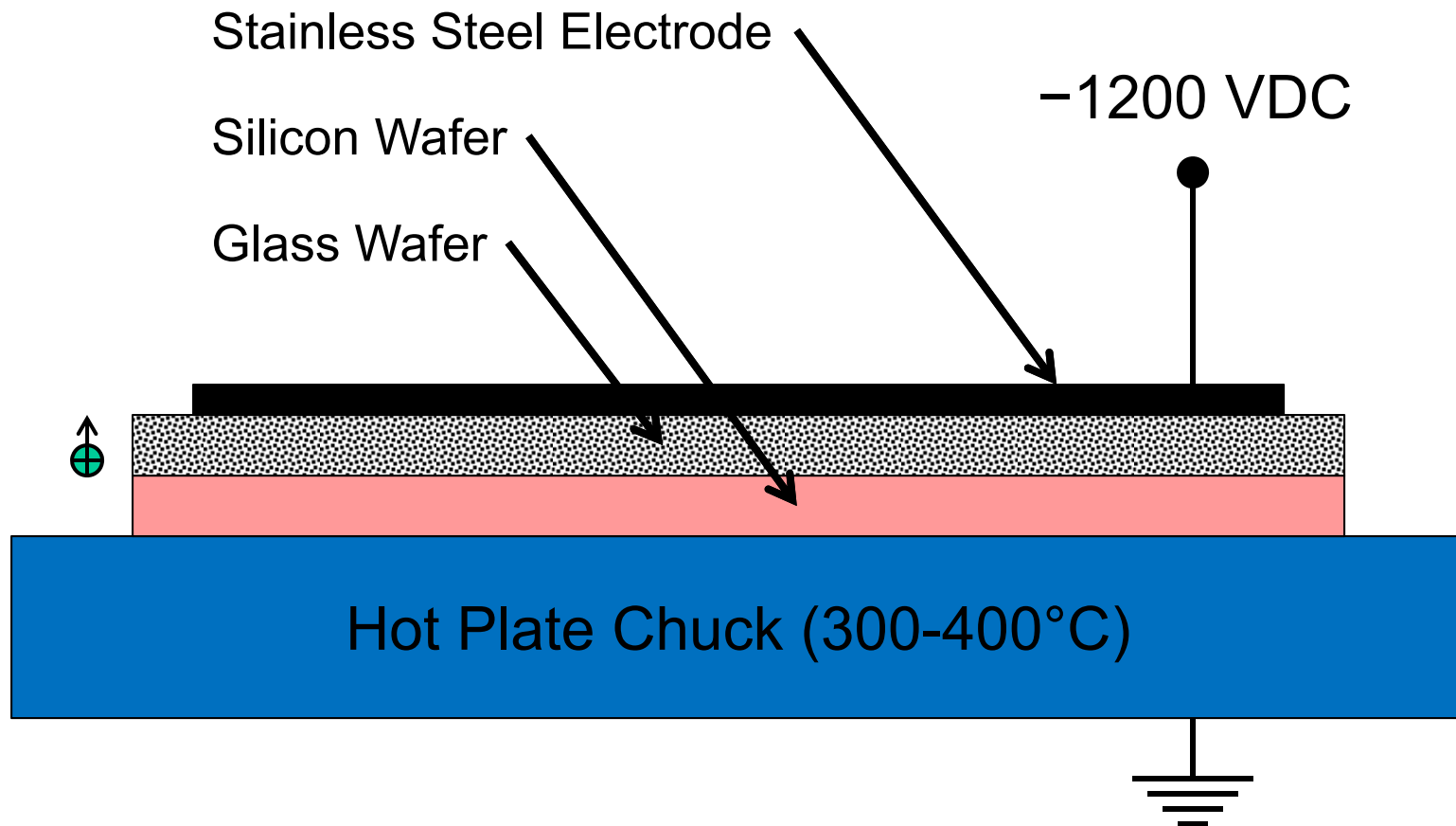
Bonding of Dissimilar Materials

- Anodic bonding of borosilicate glass to silicon
- Silicon on sapphire (SOS)
- Silicon on insulator (SOI)
- GaAs epitaxial liftoff onto silicon (GaAs/Si)
- Package frit bonding

Anodic Bonding

- Borosilicate glasses can be bonded to silicon by electrostatic attraction of cations in the glass.
- Cations can be moved through the glass with a combination of heat and applied electric field.
- Pulling the mobile cations away from the silicon-glass interface creates the electrostatic attractive force.
- Glasses that are commonly used:
 - Corning 7740 (Pyrex®)
 - Corning 7070
 - Schott 8330
 - Schott 8320
 - Iwaki 7570 (a low temperature lead/borosilicate glass)

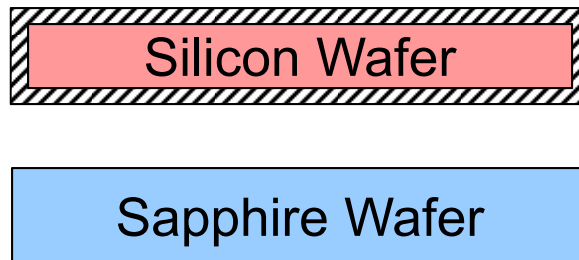
Anodic Bonding Apparatus



Silicon On Sapphire (SOS)

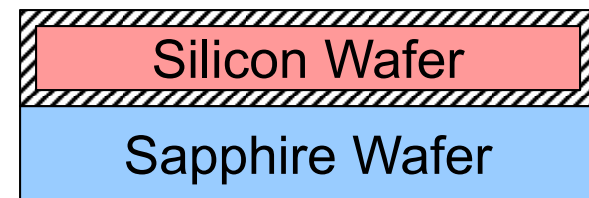
Oxidation of Silicon Wafer
Si: 300 μm ; SiO_2 : $\sim 20\text{ nm}$

1



Bonding and Annealing (270°C)

2



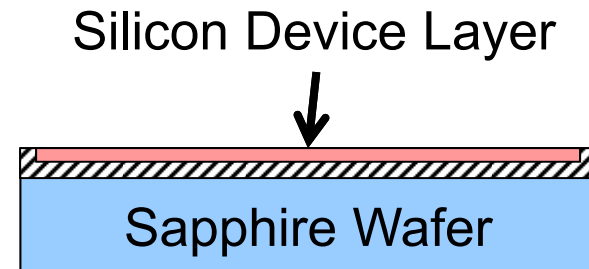
Polishing to 10 μm thick and
Etch-back to 3 μm with KOH

3



Final Polishing to 0.2 μm of Si

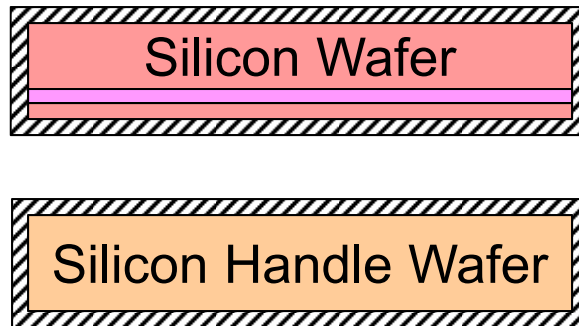
4



Bonded Silicon On Insulator (SOI)

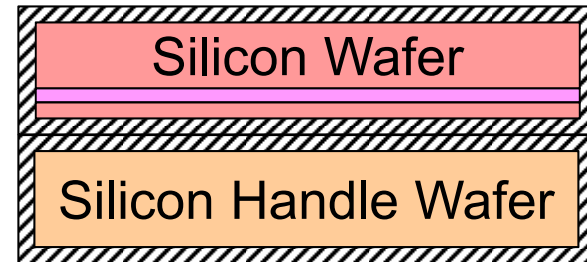
Oxidation of Silicon Wafers
& Implantation of Etch Stop

1



Bonding and Annealing

2



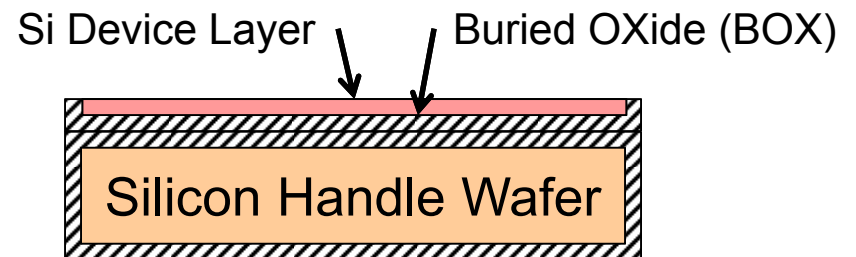
Rough Polishing and
Etching Down to Etch Stop Layer

3



Removal of Etch Stop Layer &
Final Polishing to $\sim 0.2 \mu\text{m}$ of Si

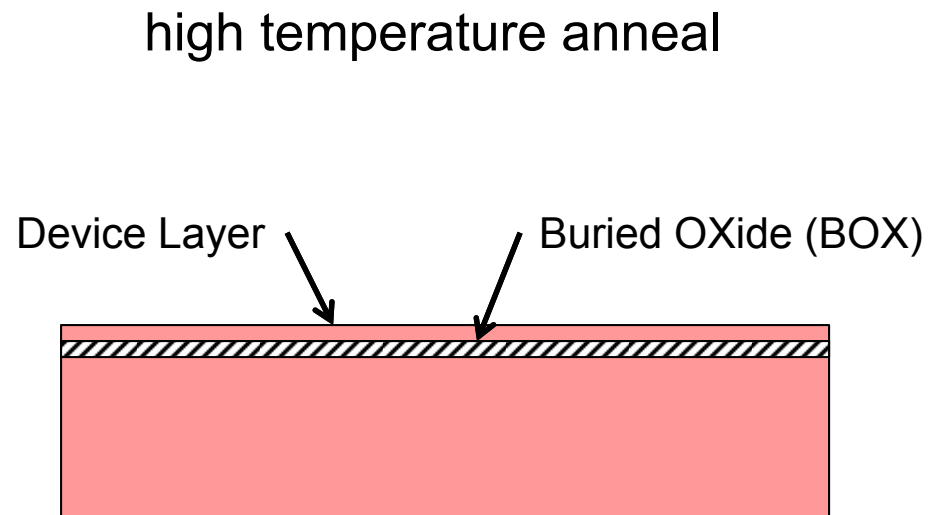
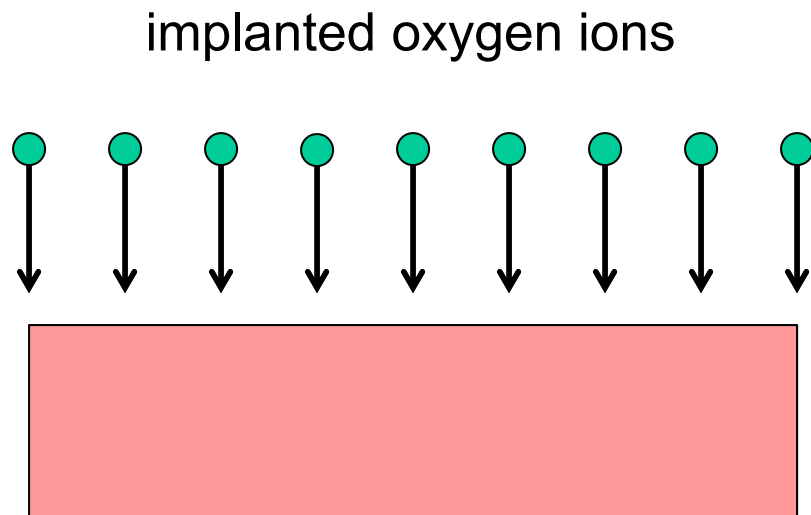
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This process was invented by J. B. Lasky of I.B.M. in 1985.

SIMOX

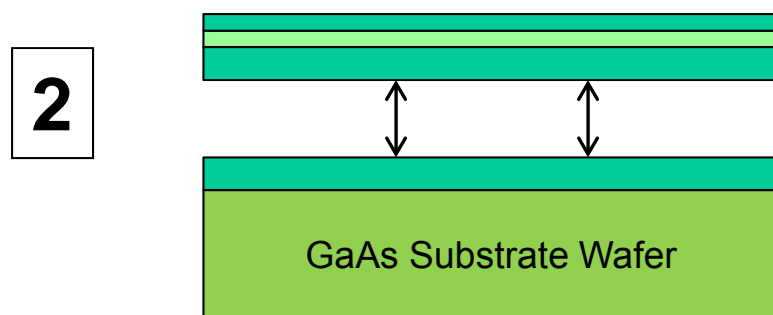
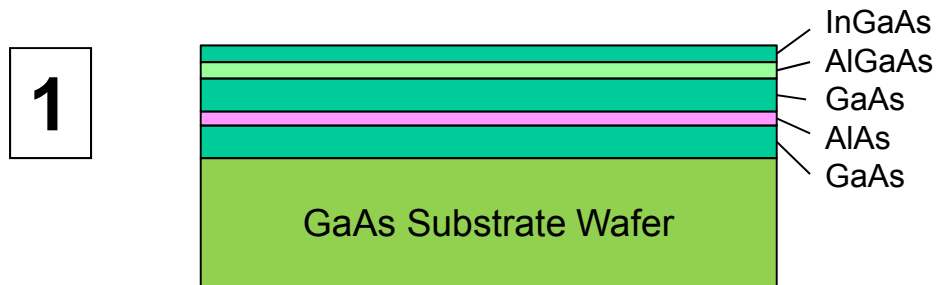
- Separation by IMplantation of OXYgen.
- A method for creating an SOI wafer without bonding.



GaAs Epitaxial Liftoff (ELO) And Bonding To Silicon

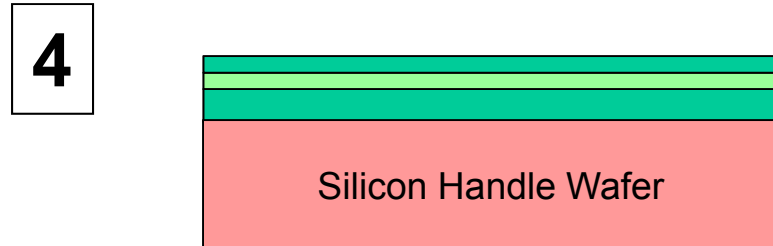
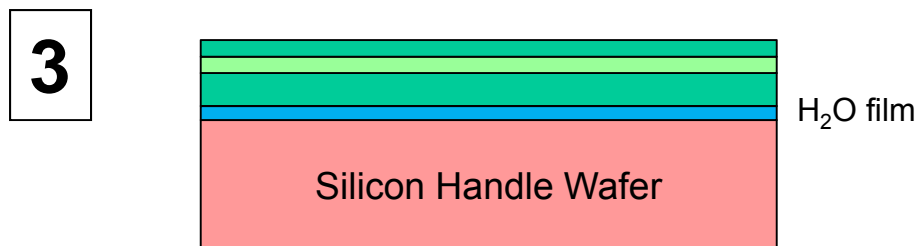
Epitaxial GaAs IC or Device is Grown over AIAs Etch Release Layer

Epitaxial GaAs IC or Device is Released by Selective HF Etching and Floated Off



Epitaxial GaAs IC or Device Layer is Floated Over to a Silicon Wafer

Assembly is Baked to Dehydrate and Strengthen the Bond



This process was invented by Eli Yablonovitch of Bell Labs in 1988.

Applications – A Bonded Pressure Sensor

